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"A Multi-Element Ultrasonic Ranging Array" describes the use of an array of multiple transducers combined with dedicated microprocessor capabilities in the development of a high resolution ultrasonic rangefinding system. The system design utilizes Texas Instruments' Ultrasonic Ranging Modules and Polaroid Electrostatic Transducers interfaced through a specially designed multiplexer to a controlling microprocessor.

The system generates a series of pulses, monitors for echo detection, and

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A MULTI-ELEMENT
ULTRA SONIC RANGING ARRAY

NAVSEA CASE 84-1233

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AND AUTONOMOUS SYSTEMS
(SEA 90G)

JANUARY 1985

NAVSEA TECHNICAL REPORT
  No. 450-90G-TR-0001

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A Multi-Element Ultrasonic Ranging Array

One of the first issues for concern in the evolution of a mobile robot design is the need to provide the system with sufficient environmental awareness so as to make possible intelligent movement. The first step towards this end consists of the acquisition of appropriate information regarding ranges and bearings to nearby objects, and the subsequent interpretation of that data. Several methods for approaching this problem have been proposed and investigated by numerous researchers, and can be broken down into two broad categories: passive devices, such as stereoscopic vision and swept-focus ranging systems, and active devices, such as laser and ultrasonic rangefinding systems. This article describes the most widely used ultrasonic ranging system employed today for this particular application, discusses some of the problems associated with its use, and then presents one method for overcoming some of these problems through the use of multiple transducers arranged in a sequentially fired array (Figure 1), with temperature compensation.

The ranging modules employed on ROBART II ("A Second Generation Autonomous Sentry Robot", ROBOTICS AGE, xxxxxxxxxx 85) were made by Texas Instruments (Figure 2) for use with the Polaroid electrostatic ultrasonic transducer, and were selected due to their low cost, high reliability, and ease of interface. An alternative system made by Massa Products Corporation (Model E-200) was evaluated but not selected because the unit cost (over $160) made this choice impractical for a multi-element array
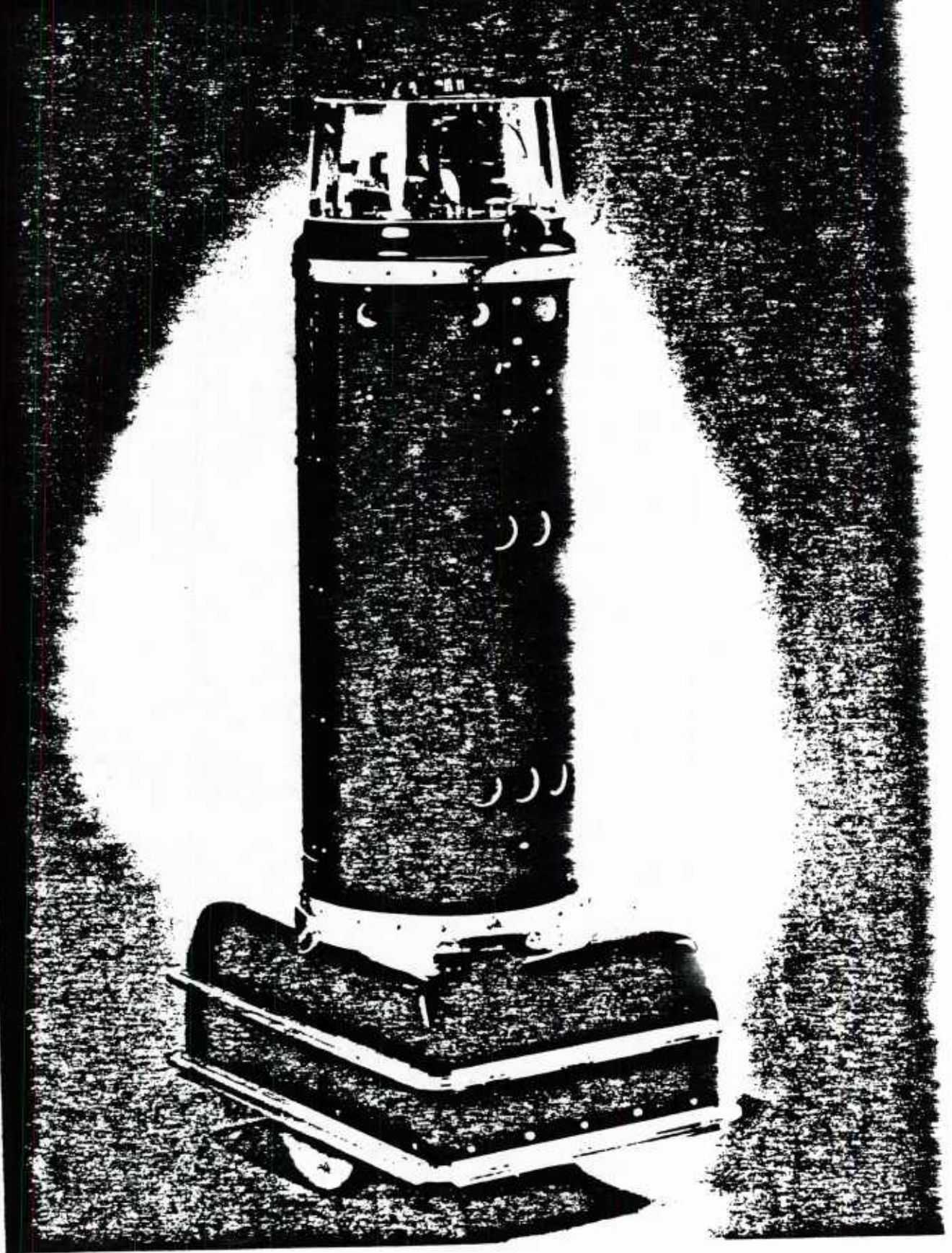
1

Figure 1. Front view photo of prototype sentry robot ROBART II, showing location of sensors in five element sequential array. The single head-mounted sensor shown was later replaced by two sensors as depicted in Figure 3. (Photo courtesy of Naval Surface Weapons Center, White Oak, MD.)

+ 5V (ORANGE)

+ 5V (YELLOW)

MFLOG (GREEN)

XLOG (BLUE)
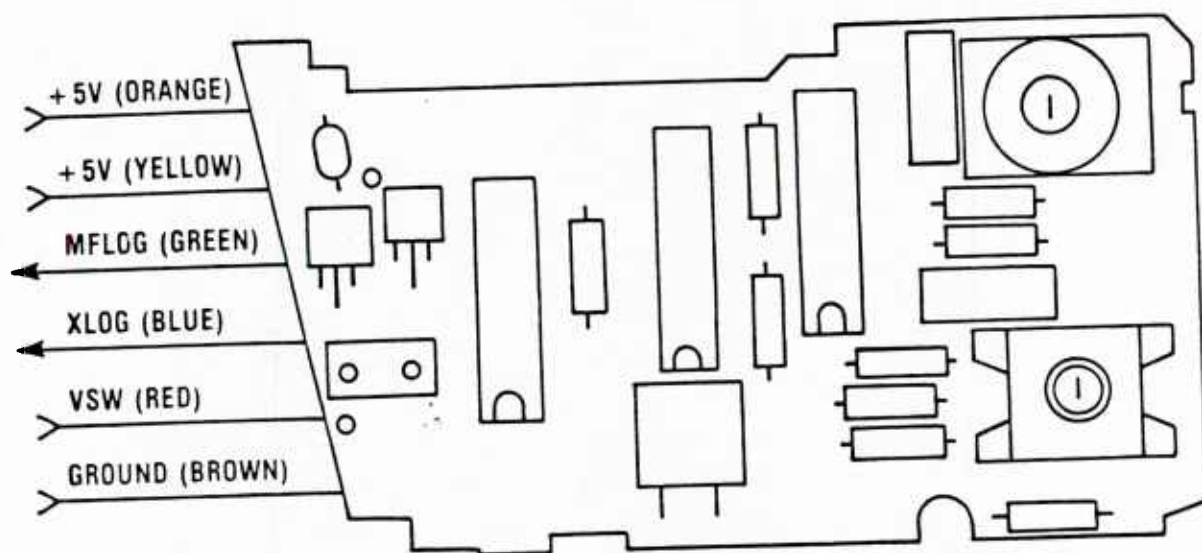
VSW (RED)

GROUND (BROWN)

Figure 2. Line drawing of the Texas Instruments Ultrasonic Ranging Module made for use with the Polaroid electrostatic transducer. Seven such boards are interfaced through a specially designed multiplexer to a single parallel port on the controlling microprocessor.

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requiring several modules. By comparison, Polaroid Corporation offers both the transducer and ranging module circuit board for only $35 a set when purchased in quantities of ten. An improved version of the circuit board, the SN28827, is now available from Texas Instruments which greatly reduces the parts count and power consumption, as well as simplifying computer interface requirements ("An Ultrasonic Ranging System", BYTE, October 84).

The Polaroid ranging module is an active time-of-flight device developed for automatic camera focusing, and determines the range to target by measuring elapsed time between the transmission of a "chirp" of pulses and the detected echo. The "chirp" is of one millisecond duration and consists of four discrete frequencies transmitted back-to-back: 8 cycles at 60kHz, 8 cycles at 56kHz, 16 cycles at 52.5kHz, and 24 cycles at 49.41kHz. This technique is employed to increase the probability of signal reflection from the target, since certain surface characteristics could in fact cancel a single-frequency waveform, preventing detection. It should be recognized, however, that the one millisecond length of the "chirp" is a significant source of potential error, in that sound travels roughly 1100 feet per second at sea level, which equates to about 13 inches per millisecond. The uncertainty and hence error arises from the fact that it is not known which of the four frequencies making up the "chirp" actually returned to trigger the receiver, but timing the echo always begins at the start of the "chirp."

A second very important characteristic of the Polaroid system is the use of a stepped gain control in the receiver section, where both the gain and the Q of the amplifier are

increased as a function of time following "chirp" transmission. This ensures a high signal-to-noise ratio while matching the relative amplification level to the strength of the returned echo, which decays rapidly as a function of distance (and hence time). This becomes an important factor in the design of an array of sequential emitters, where residual or multiple echos could easily confuse the next element in the array. A faint residual echo generated by a previous "chirp" of another sensor would be in all probability too weak for detection by the now active rangefinder since its own gain had not yet been increased to the required level.

To understand the advantages of the sequential array it is necessary to have a good feel for the strengths and weaknesses of ultrasonic ranging in general, keeping in mind that the ultimate goal is to be able to repeatedly obtain accurate range information on objects surrounding a mobile platform. This dictates that power consumption be kept to a minimum and that the system be capable of operating in real time, where real time depends to some extent on how fast the robot travels. These two constraints make a mechanically positioned sensor less than desirable, in that precious time and energy are wasted while the sensor is being repositioned to take ranges in a new direction. The ideal solution would be to employ a multitude of prepositioned transducers that could be individually selected at will, thus enabling the robot to get range information in any given direction at any particular time. Since in reality there is associated with each sensor some overhead in terms of physical
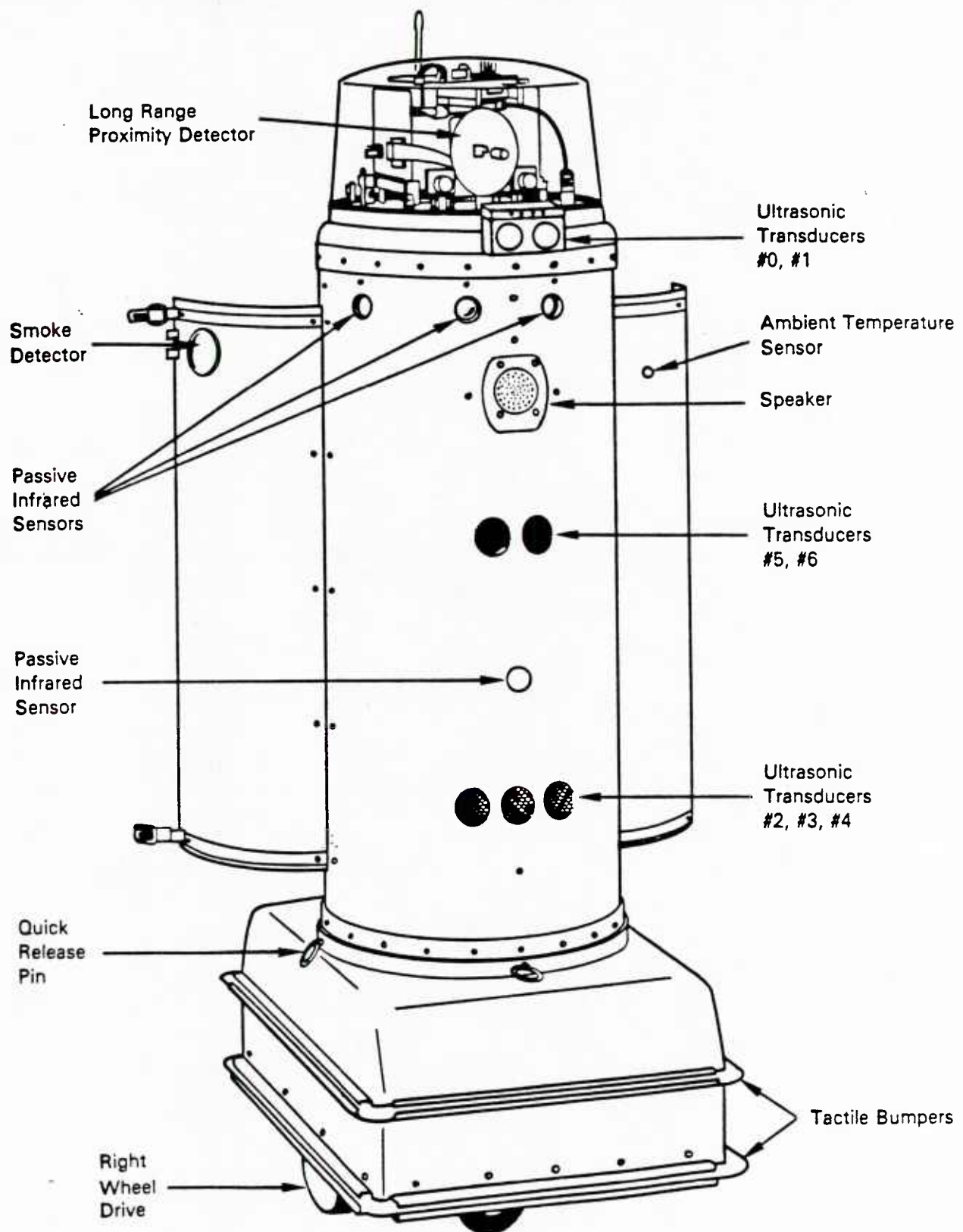
5

Figure 3. Front view line drawing depicting the location of various sensors which provide the robot with information on its environment. Temperature sensor at right in diagram on left access door provides information to correct for the temperature dependence of the speed of sound in air.

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space requirements, power consumption, interface circuitry, and acquisition cost, an array size of five transducers was chosen for implementation on ROBART II (Figure 3). In addition, two more sensors were mounted on the robot's head, which is positionable up to 100 degrees either side of centerline. This configuration complements the fixed array for rangefinding outside its area of coverage.

For any ultrasonic ranging system there exists a multitude of error sources that must be understood and taken into account. In Figure 4 it is shown that the speed of sound in air is proportional to the square root of temperature in degrees Rankine, which for the temperature variations likely to be encountered in this application, results in a significant effect even considering the short ranges involved. Temperature variations over the span of 60 to 80 degrees F can produce a range error as large as 7.8 inches at a distance of 35 feet. Fortunately, this situation is easily remedied through the use of a correction factor based upon the actual room temperature, available to ROBART II with an accuracy of 0.5 degrees F from an external sensor mounted on the left access door. This sensor (Industrial Computer Designs, Remote Temperature Sensor RTS-1) produces an output voltage which varies from .80 to 4.80 volts over the temperature range of 20 to 120 degrees F, and is interfaced to the system through an eight-bit analog-to-digital converter (Figure 5). The ranging units are calibrated at standard room temperature (70 degrees F), and then the correction factor is applied to adjust for actual conditions. The formula is simply: actual range equals measured range times the correction

Speed of Sound $= \sqrt{g_c\, k\, R\, T}$

Where:
- c = speed of sound (feet/second)
- g_c = gravitational constant
- k = ratio of specific heats (for air = 1.4)
- R = gas constant for a specific gas
- T = temperature (degrees Rankine)

Substituting in appropriate values for air yields:

$$c = \sqrt{(32.3)(1.4)(53.3)\,T} = 49.018\sqrt{T} \quad \text{ft/sec}$$

Which says the speed of sound in air is proportional to the square root of local temperature, in degrees Rankine (degrees Farenheit + 460 degrees).

At 70 degrees F: $c = 49.018\sqrt{460 + 70} = 1128$ ft/sec

At 30 degrees F: $c = 49.018\sqrt{460 + 30} = 1085$ ft/sec

Distance d traveled in feet over time t seconds is given by:

$d = ct$ which yields:

$d_A / c_A = t = d_S / c_S$

where subscripts S and A denote "standard" and "actual" conditions, respectively.

Thus the formula for the actual distance measured by an ultrasonic ranging unit calibrated at standard temperature T_S is:

$$d_A = (d_S)(c_A/c_S) = d_S\sqrt{T_A / T_S}$$

As an example, for a system calibrated at 80° F operating at an actual temperature of 60° F, a measured range of 35 feet corresponds to an actual range of

$$d_A = 35\sqrt{\frac{460 + 60}{460 + 80}} = 34.35 \text{ feet}$$

For an error of 7.8 inches

Figure 4.   Derivation of the temperature dependence of the speed of sound in air. The effects of humidity on k and R are considered insignificant for this discussion.
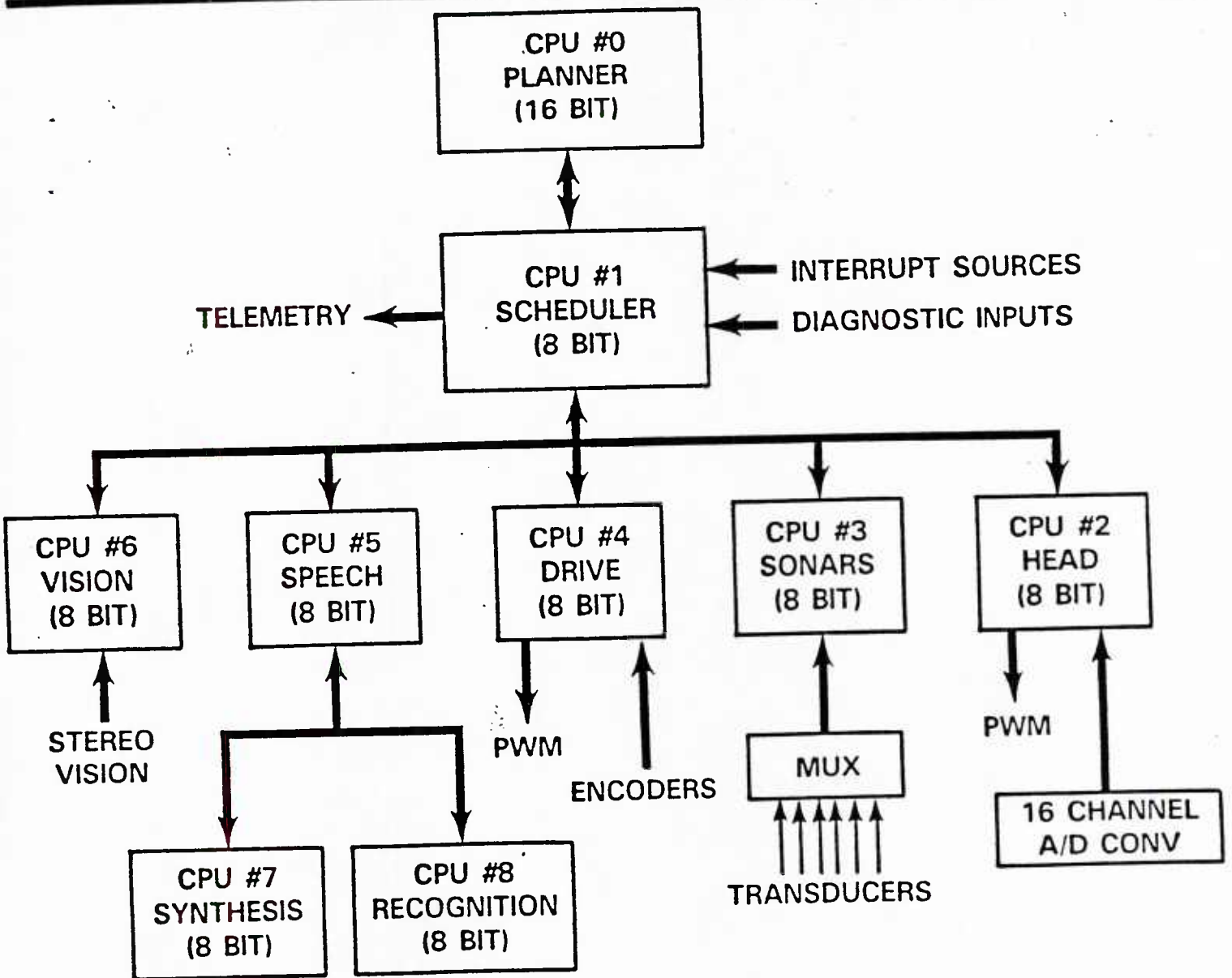
SYSTEM ARCHITECTURE - ROBART II

Figure 5. Control hierarchy for ROBART II. The ambient temperature sensor is interfaced to CPU #2 via a 16 channel A/D converter. The 7 ranging modules are interfaced to CPU #3 through a special multiplexing circuit which allows them to be individually activated in sequence upon command from the Scheduler.

factor, where the correction factor is the square root of the ratio of actual temperature to standard temperature, in degrees Rankine. The possibility does still exist, however, for temperature gradients between the sensor and the target to introduce range errors, in that the correction factor is based on the actual temperature near the sensor only.

All other sources of error can be attributed to properties of the target itself, the transducer, or the timing and processing circuitry and software. Previously it was mentioned that the one millisecond length of the transmitted "chirp" introduced an uncertainty into the timing process. In addition, random electrical or ultrasonic noise, if not properly discriminated by the receiver circuitry, can lead to erroneous information. But for the most part it can be shown that the more significant errors arise from the various ways the ultrasonic beam emitted by the transducer interacts with the target, as discussed below.

The width of the beam is determined by the transducer diameter and the operating frequency. The higher the frequency of the emitted energy, the narrower and more directional the beam, and hence the higher the angular resolution. Unfortunately, an increase in frequency also causes a corresponding increase in signal attenuation in air, and decreases the maximum range of the system. For the Polaroid transducers the chosen frequencies which make up the "chirp" result in a beam width of approximately thirty degrees. Best results are obtained when the beam centerline is maintained normal to the target surface. As the

angle of incidence varies from the perpendicular, however, note that the range actually being measured does not always correspond to that associated with the beam centerline, as shown in Figure 6. The beam is reflected first from that portion of the target that is closest to the sensor. In fact, at a distance of 15 feet from a flat target, with an angle of incidence of 70 degrees, the theoretical error could be as much as 10 inches, in that the actual line of measurement intersects the target surface at point B' as opposed to point A. The problem is further complicated for surfaces of irregular shape.

The width of the beam introduces an uncertainty in the perceived distance to an object from the sensor, but an even greater uncertainty in the angular resolution of the object's position. A very narrow vertical target such as a long wooden dowel maintained perpendicular to the floor would have associated with it a relatively large region of floor space that would essentially appear to the sensor to be obstructed. Worse yet, an opening such as a doorway may not be discernable at all to the robot when only six feet away, simply because at that distance the beam is wider than the door opening. In fact, using a one inch diameter vertical dowel as a target, the effective beam width of the Polaroid system was found to be 36 inches at a distance of only 6 feet from the sensor. The doorway detection problem is illustrated in Figures 10 and 11.

Another significant error occurs when the angle of incidence of the beam decreases below a certain critical angle, and the reflected energy does not strike the transducer (Figure 7). This
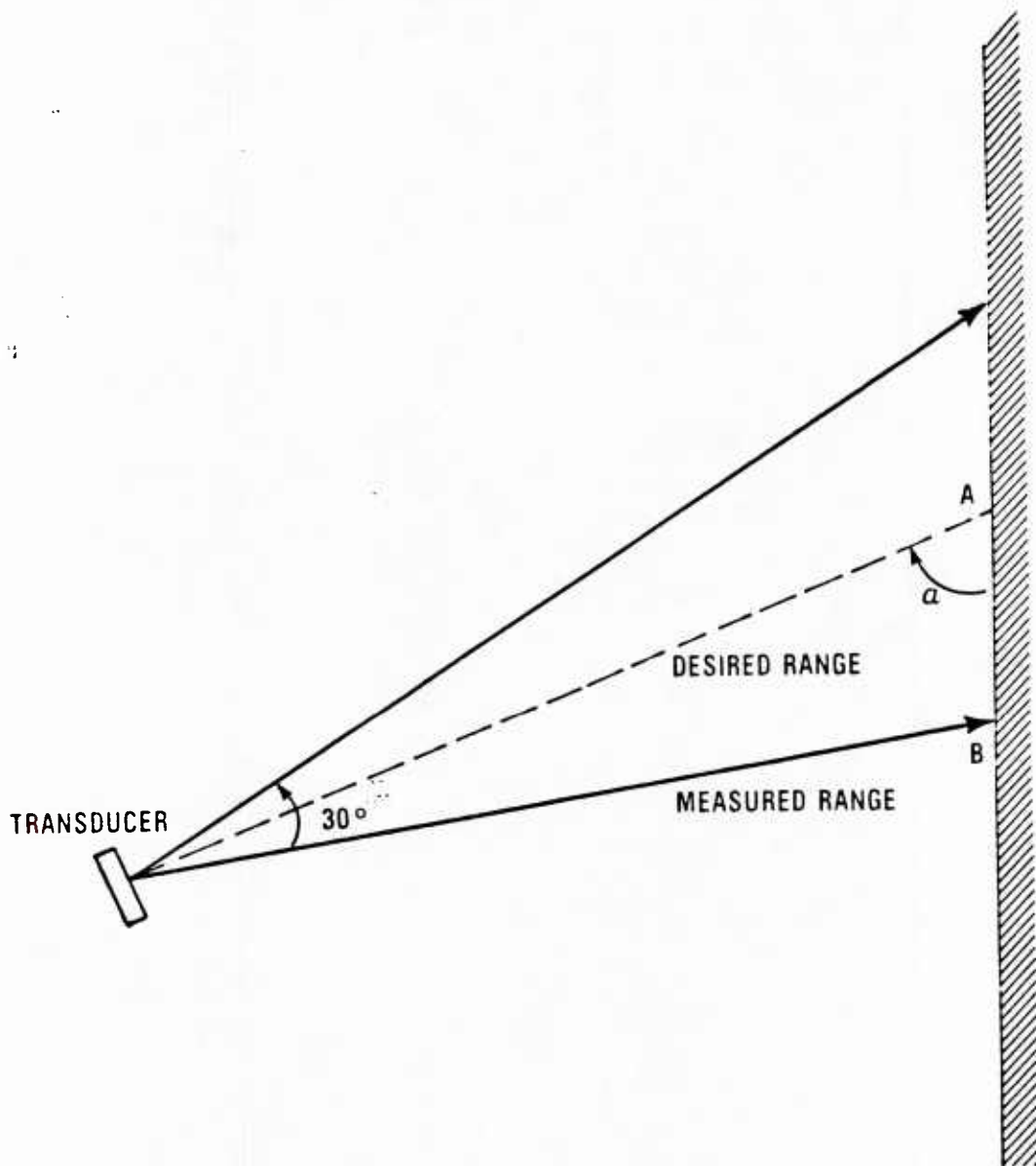
11

Figure 6. Due to beam divergence, ultrasonic ranging works best when the beam centerline is maintained normal to the target's surface. For off normal conditions, the range measured does not always correspond to that associated with the beam centerline.
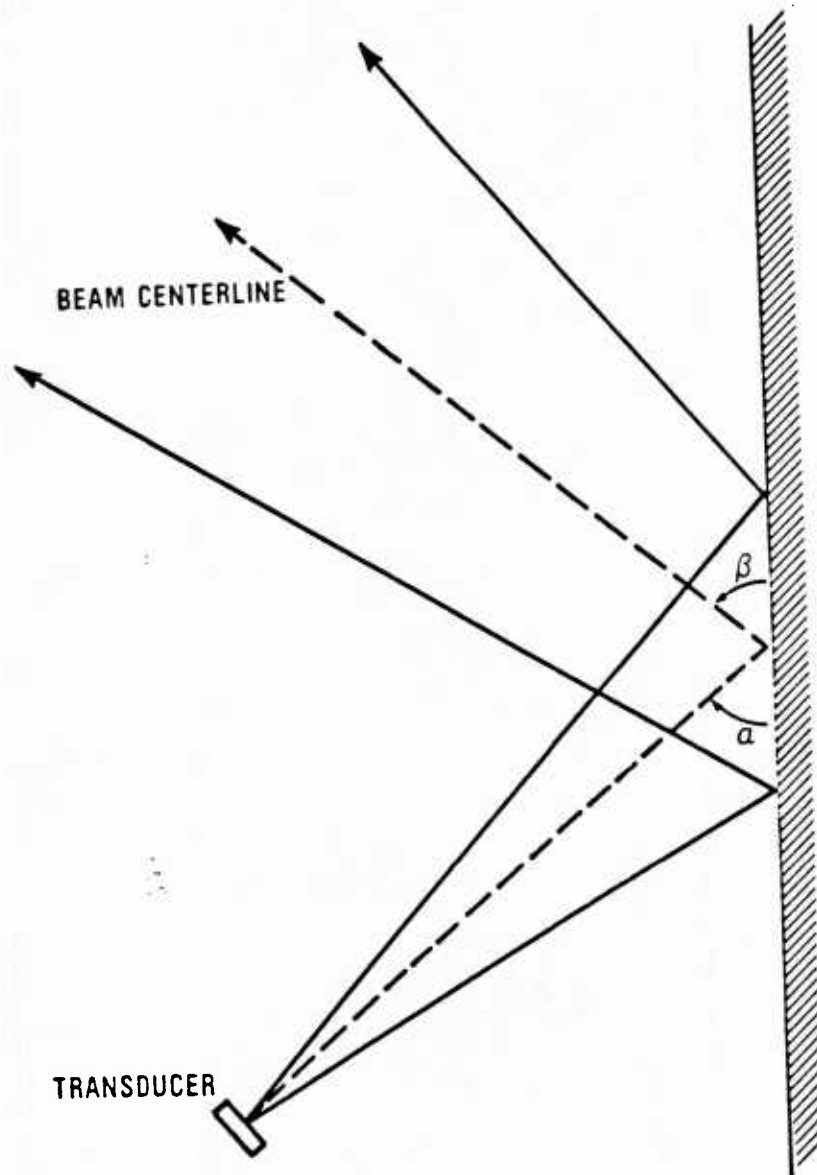
Figure 7. As the angle of incidence decreases below a certain critical angle, the reflected energy will not be detected by the transducer, resulting in erroneous range information. For specular reflection from smooth surfaces, the angle of reflection β is equal to the angle of incidence α.

occurs because most targets are specular in nature with respect to the relatively long wavelength (roughly 1/4 inch) of ultrasonic energy, as opposed to being diffuse. In the case of specular reflection, the angle of reflection is equal to the angle of incidence, whereas in diffuse reflection energy is scattered in various directions, caused by surface irregularities equal to or larger than the wavelenth of incident radiation. The critical angle is thus a function of the operating frequency chosen, and topographical characteristics of the target. For the sensors used on ROBART II this angle turns out to be approximately 65 degrees for a flat target surface made up of unfinished plywood. In Figure 8 the ranging system would not see the target and indicate instead maximum range, whereas in Figure 9 the range reported would reflect the total roundtrip through points A, B, and C as opposed to just A and B.

The relatively long range capability (approximately 35 feet) of the Polaroid system makes it well suited for gathering range data for both navigational planning and collision avoidance. Navigational planning involves making a determination of where the robot is, and in addition its particular orientation in that spot, as well as the subsequent calculation of appropriate commands to move the robot to a new location and orientation. The simplest case reduces the problem to two dimensions with a priori knowledge of the surroundings in the form of a memory map, or world model. The task becomes one of trying to correlate a real-world sensor-generated image to the model, and extracting position and orientation accordingly. Several factors complicate the problem.
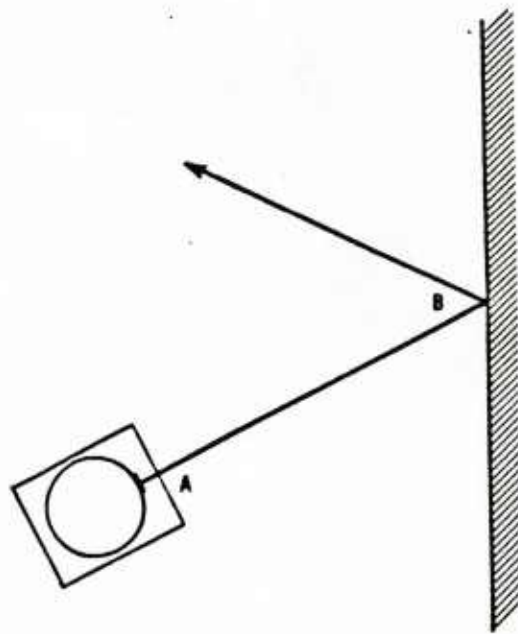
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Figure 8.   For smooth surfaces, the ranging system will not see
the wall ahead of the robot, and will erroneously indicate
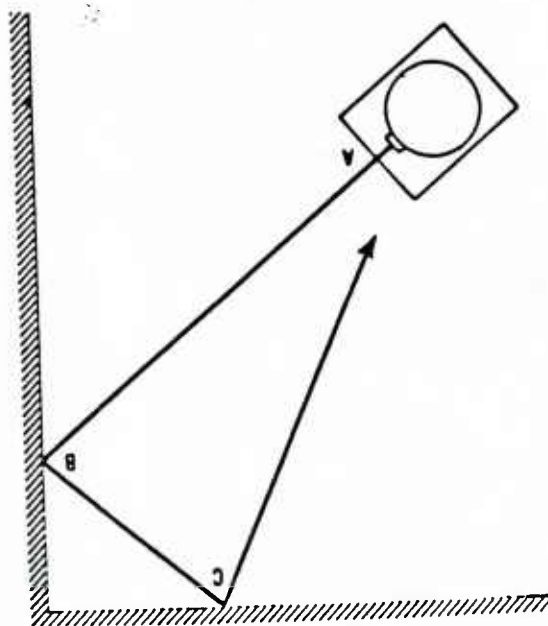maximum range instead.

Figure 9.   The measured range will reflect the round trip
distance   through points A, B,   and C as opposed to the actual
distance from A to B.

For one thing, the real environment is three-dimensional, and although the model represents each object as its projection on the X-Y plane, the sensor may see things differently, which complicates the task of correlation. Secondly, the computational resources required are large, and the process is time consuming, requiring the robot at times to "stop and think". Also, the acquisition of the data itself can take several seconds using ultrasonic ranging techniques, due to the relatively slow velocity of soundwaves in air. More importantly for the purposes of this discussion, however, are the effects of the various error sources previously described, which can collectively impede a solution altogether.

Figure 10 depicts the results of 256 range values taken by a single sensor mounted on the head of ROBART II, with the robot situated approximately 5 feet from the wall as shown. The data took approximately 7 seconds to collect as the head was mechanically repositioned between rangings. The process could have been speeded up to some extent by reducing the number of range readings taken while the head was scanning. Note, however, in Figure 10 that only two positions of the head allowed the beam to pass through the doorway. Had the number of positions been reduced from 256 to 100, it is possible that the doorway would have escaped detection altogether.

The resulting plot is of exceptional quality primarily due to the nature of the walls themselves, which were located in a basement room with exposed studs, thereby providing excellent beam return properties. The proper identification of the open

Figure 10. Plot of 256 range readings taken by a single mechanically positioned sensor mounted on the head of ROBART II. An open doorway is detected in the wall approximately 5 feet directly ahead of the robot. Note the excellent correlation with the actual wall location. (Plot courtesy of Artificial Intelligence Laboratory, MIT.)

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doorway, and the excellent correlation with the actual map would provide the robot with a highly accurate "fix". It should be noted, however, that the room was fairly uncluttered, as is not always the case in reality. In Figure 11 the robot was repositioned 7 feet away from the wall, and unable to detect the opening. For situations such as this the robot needs help from other types of sensors.

Collision avoidance is a little easier to address in that accuracies are less important and the computational overhead nowhere near as great. The intent is simply to be aware of obstructions in time to alter course to avoid them, assuming for the time being that the issue of updating the world model to reflect their presence is deferred until later. For this application the sequential array can improve performance over a single sensor in several ways. As previously discussed, the array allows for range measurements to be made in many different directions very quickly with minimal power consumption. A second advantage comes from the inherent ability to employ beam splitting techniques to improve the angular resolution, already shown to be extremely poor for a single transducer.

Beam splitting involves the use of two or more rangefinders with partially overlapping beam patterns. Figure 12 shows how for the simplest case of two transducers, twice the angular resolution can be obtained along with a 50 percent increase in coverage area. The technique is extremely simple: if the target is detected by both sensors A and B, then it (or at least a portion of it) must lie in the region of overlap shown by the shaded area. If detected by A but not B, then it lies in the

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Y-AXIS (FEET)
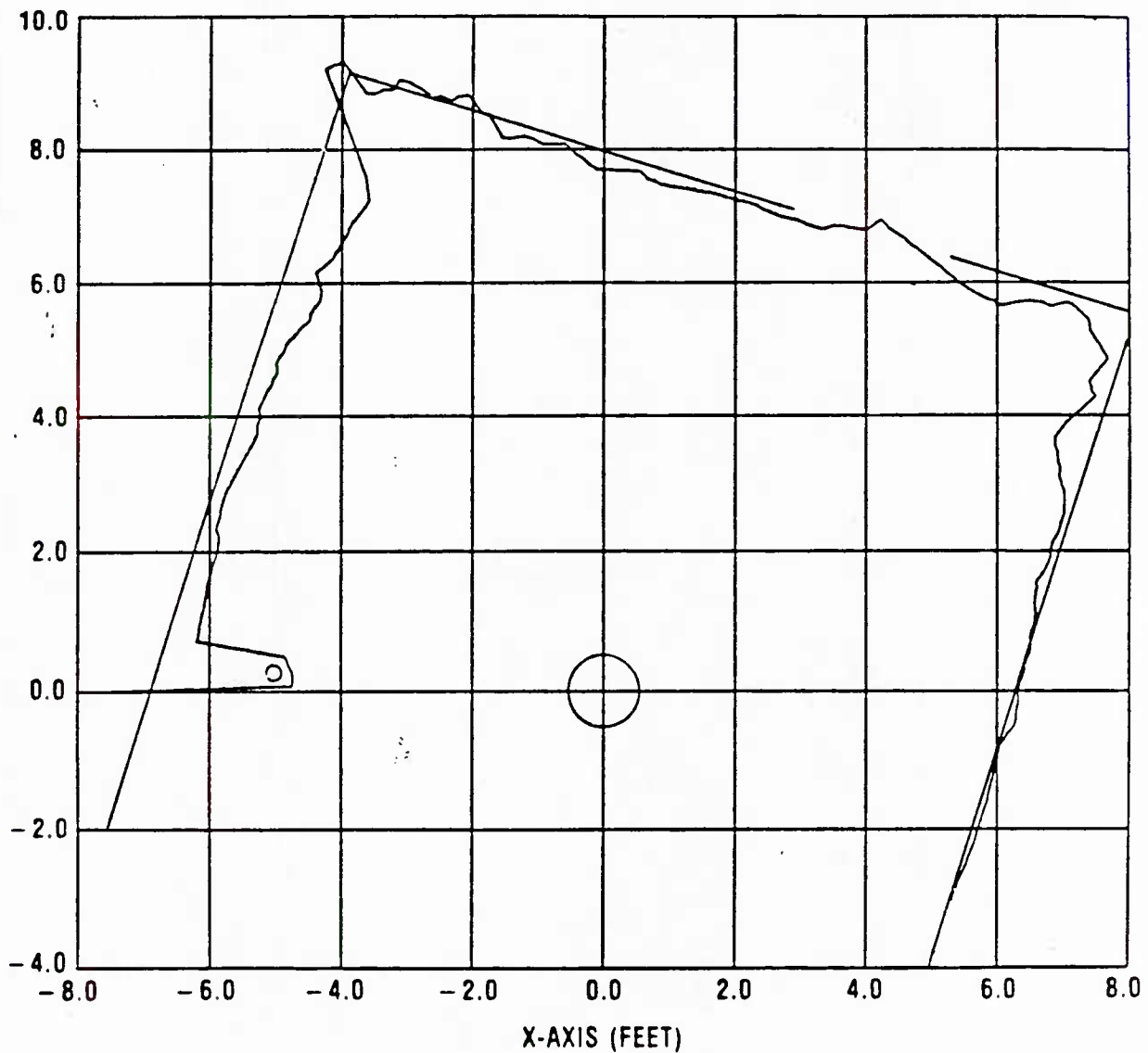
SONAR PLOT 3 — BASEMENT — 29 MARCH 84

X-AXIS (FEET)

Figure 11. Plot of same room with the robot now situated approximately 7 feet from wall. Due to beam divergence the doorway is no longer detectable simply because at that distance the beam is wider than the door opening. The 256 range readings took approximately 7 seconds to collect. (Plot courtesy of Artificial Intelligence Laboratory, MIT.)

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FOR A SINGLE SENSOR
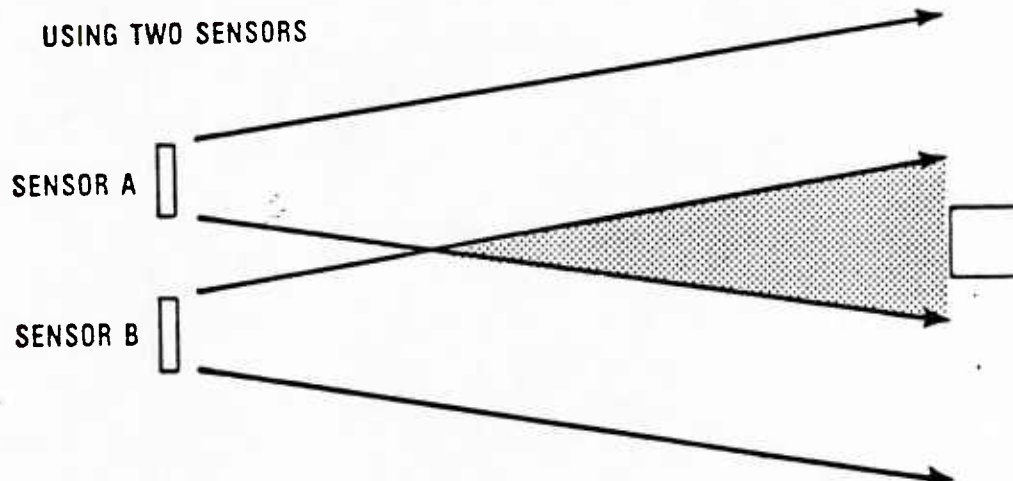
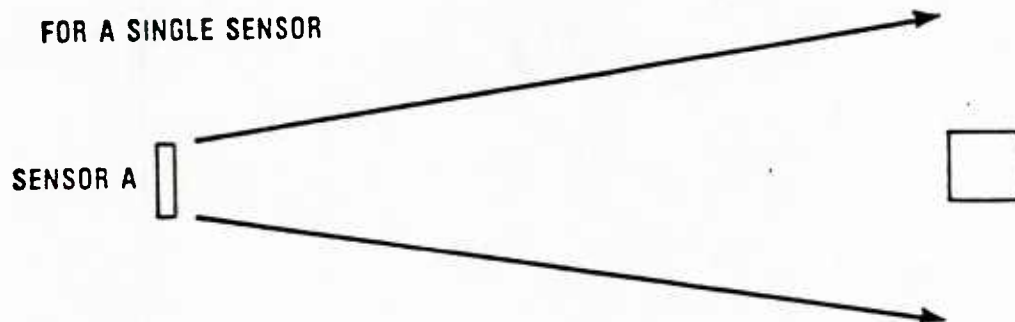SENSOR A

USING TWO SENSORS

SENSOR A

SENSOR B

Figure 12. Beam splitting techniques using two sensors can improve angular resolution by a factor of two while increasing the area of coverage by 50 percent. Further improvements can be gained by increasing the number of sensors with overlapping beam patterns.

region at the top of the figure, and so on. Increasing the number of sensors with overlapping beam patterns decreases the size of the respective regions, and thus increases the angular resolution. The sensor pattern employed in the array used on ROBART II allowed for an angular resolution of 2 degrees when locating a one inch vertical dowel 9 feet from the robot, a significant improvement over the 30 degree resolution of a single transducer.

It should be noted, however, that this increase in resolution is limited to the case of a discrete target in relatively uncluttered surroundings, such as a metal pole supporting an overhead load, or a box in the middle of the floor. No improvement is seen for the case of an opening smaller than an individual beam width, such as the doorway illustrated in Figure 11. The entire beam from at least one sensor must pass through the opening without striking either side in order for the opening to be detected, and the only way to improve resolution otherwise is to decrease the individual beam widths by changing transducers or through acoustical focusing, which normally is impractical. Nevertheless, the sequential array provides a means of covering a much larger area in a shorter amount of time, in most cases with far better resolution, when employed for purposes of collision avoidance.

Just as the information gathered by the array can be used to avoid an object in the path of the robot, it can also be used to move towards or even "follow" an object. As ranges are repeatedly obtained along fixed bearings fanning out in the direction of

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travel, it is a fairly simple matter to track a specified target within the field of view even while both the target and robot are in motion. This technique is employed on ROBART II when in the sentry mode to acquire and then track an intruder detected by any of the system's many intrusion sensors. The robot's mean forward velocity is adjusted as a function of range to the target, and then a calculated differential in left and right drive motor speeds is introduced as a function of how far off centerline the target appears. This causes the robot to turn towards the target being followed in a controlled fashion, until it appears centered, all the while maintaining a specified interval.

The ultrasonic transducers on ROBART II are mounted from the inside of a 13 inch diameter section of plastic pipe which forms the upper body housing. In order to achieve the desired fanout angle of 9 degrees between beam centerlines for adjacent units, the mounting holes had to be staggered, essentially creating two rows, with three sensors on the bottom row and two on the top. To increase the vertical coverage somewhat the top row was situated 11 inches above the bottom row, which in turn is located 18 inches above the floor. Additional vertical coverage can be gained if one of the head mounted sensors is positioned on centerline and operated in conjunction with the array, thus providing maximum protection in the direction of travel for the full height of the robot.

To simplify the circuitry involved, all timing and time-to-distance conversions are done in software. Three control lines are involved in the interface of the Polaroid ultrasonic
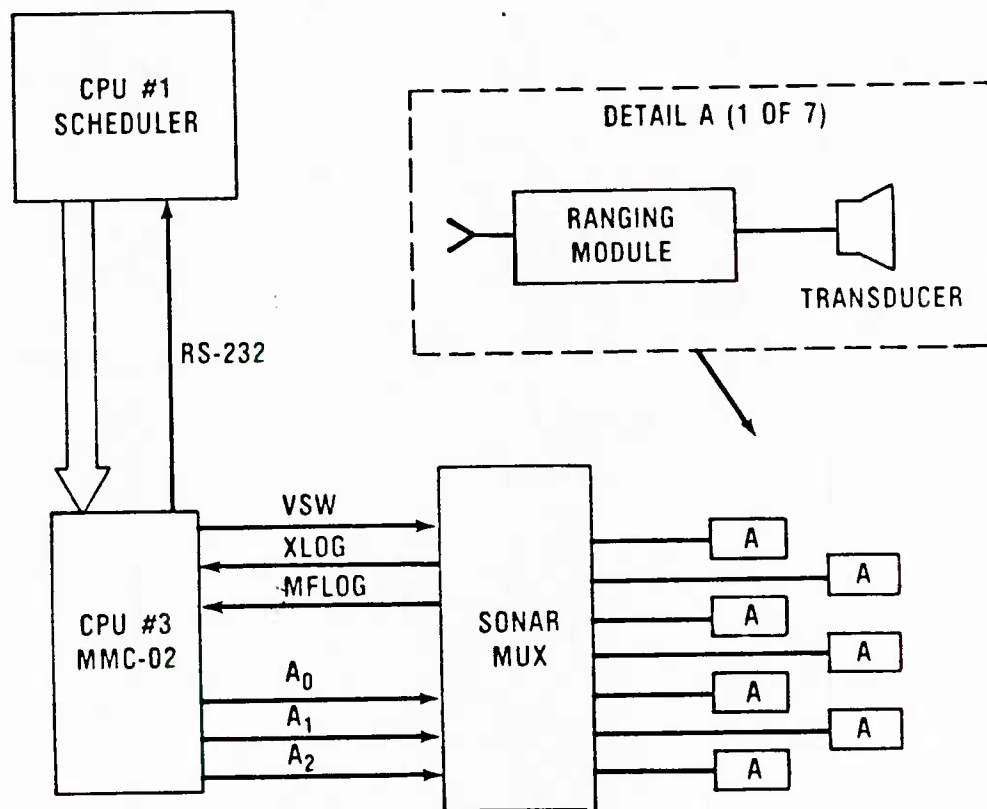
Figure 13. Block diagram of the multiplexed ultrasonic ranging system. CPU #3 "sees" only one ranging unit at a time, sequentially activating the modules upon command from the Scheduler. Stored ranges are transmitted up the hierarchy at the end of the sequence, which is then repeated.

circuitboard to a microprocessor. The first of these, referred to as VSW (Figure 13) initiates operation when brought high to +5 volts. A second line labelled XLOG signals the start of pulse transmission, while the line labelled MFLOG indicates detection of the first echo. The controlling microprocessor must therefore send VSW high, monitor the state of XLOG and commence timing when transmission begins (approximately 5 milliseconds later), and then poll MFLOG until an echo is detected or sufficient time elapses to indicate there is no echo.

Since sound travels rather slowly in air, a lot of CPU time will be wasted waiting for echos, and fast range update rates will effectively tie up the microprocessor and interfere with other tasks. Fortunately, however, small dedicated controllers which can be slaved to the master microprocessor are readily available at low cost, and all-CMOS versions feature low power consumptions which make them attractive alternatives to specialized circuitry. ROBART II employs a 65SC02-based MMC-02 controller manufactured by R.J. Brachman Associates which is ideal for this task, designated as CPU #3 (Figure 5). Two 65SC22 Versatile Interface Adapters provide 32 general purpose I/O lines as well as 8 handshake/control lines, with an 8 kilobyte onboard address space. Total power consumption is less than 35 milliamps.

The 7 ultrasonic ranging units are interfaced to CPU #3 through a three-circuit eight-channel multiplexer utilizing 4051 analog switches operating in the digital mode, as shown in Figure 14. This way the microprocessor "sees" only one ranging unit at a time through the multiplexer, and the software merely executes in a loop, incrementing each time the index which enables a specific
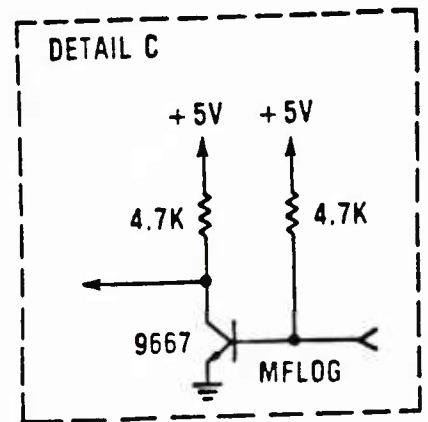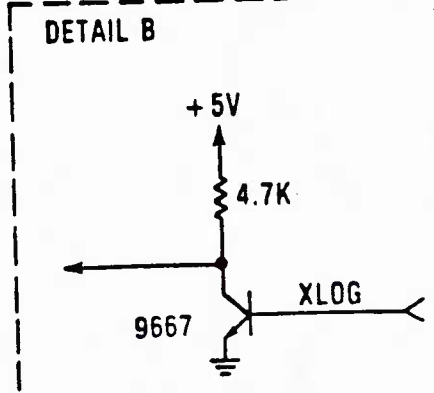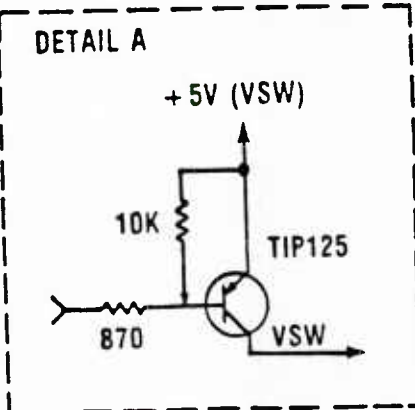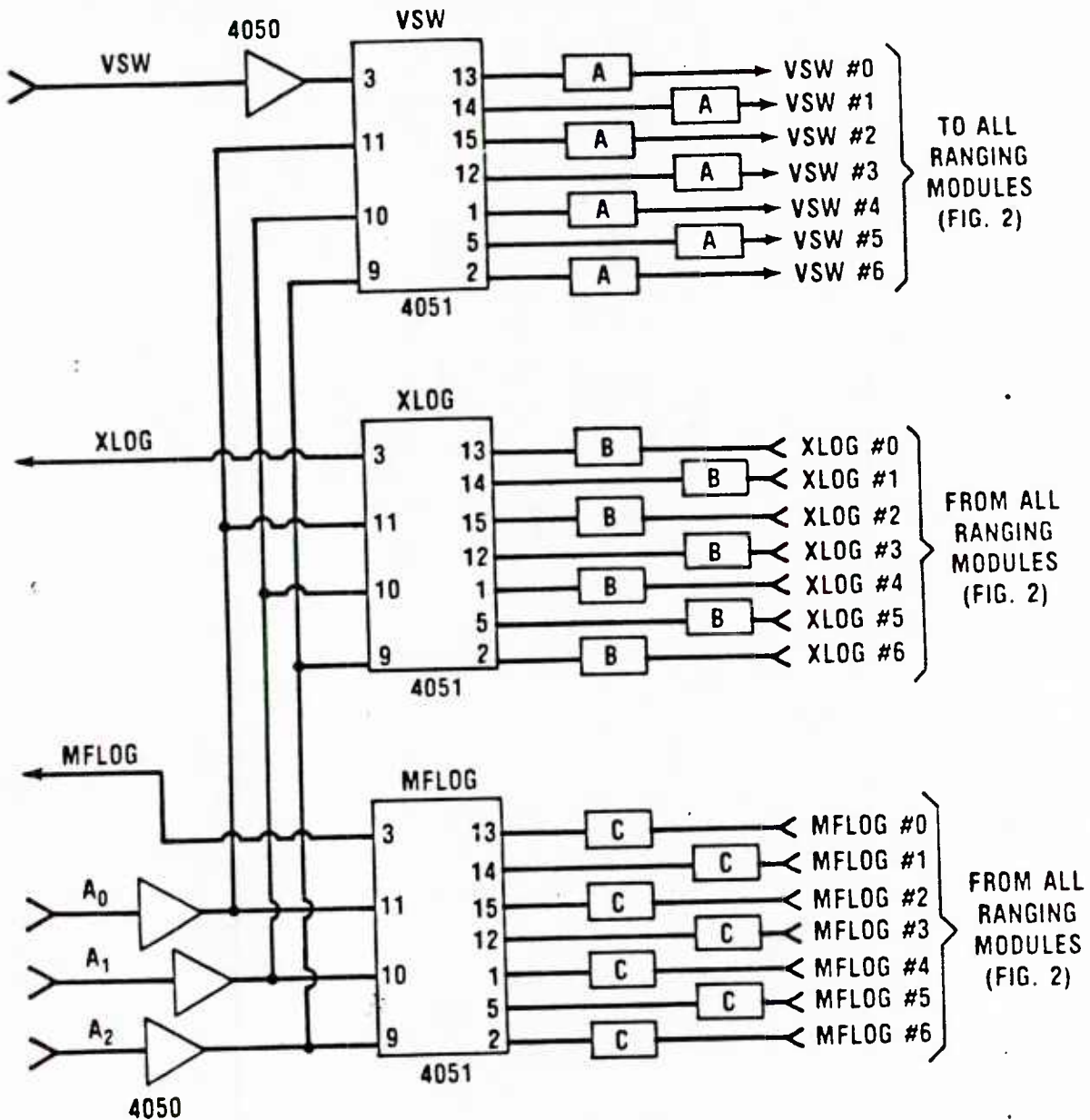
24

Figure 14. Schematic diagram for the multiplexer interface. The 4051 analog switches are operated in the digital mode with pins 6 and 7 grounded. Only one channel at a time is enabled, determined by the binary number on select lines A0, A1, and A2, set by CPU #3.

ranging unit. Three I/O lines from the MMC-02 handle this enabling function, activating simultaneously the 4051 multiplexers for VSW, XLOG, and MFLOG. The binary number placed on these I/O lines by the microprocessor determines which channel is selected, all other channels assume a high impedance state. Three other I/O lines carry the logic inputs to the microprocessor from the multiplexers for XLOG and MFLOG, and from the microprocessor to the multiplexer for VSW. A final I/O line on the same port is used to power down the interface circuitry and the ranging units when not in use to save battery power. The ranging module circuitboards, CPU #3, and the multiplexer board are depicted in the photo of the robot's removable electronics package, Figure 15.

A second parallel port on the MMC-02 is used to receive commands from the Scheduler which tell CPU #3 to power up the ranging units, and then which sensors to sequentially activate. Commands are in the form of an eight-bit binary number represented in hexadecimal format, where the upper nibble represents the starting ID and the lower nibble the ending ID for the sequence. For example, the command #16 would mean activate and take ranges using sensors #1 through #6 sequentially, whereas the command #44 would cause only sensor #4 in the array to be repeatedly activated. Each time through the loop upon completion of the sequence, the stored ranges are transmitted up the hierarchy to the Scheduler over an RS-232 serial link, with appropriate handshaking. The sequence is repeated in similar fashion until such time as the Scheduler sends a new command
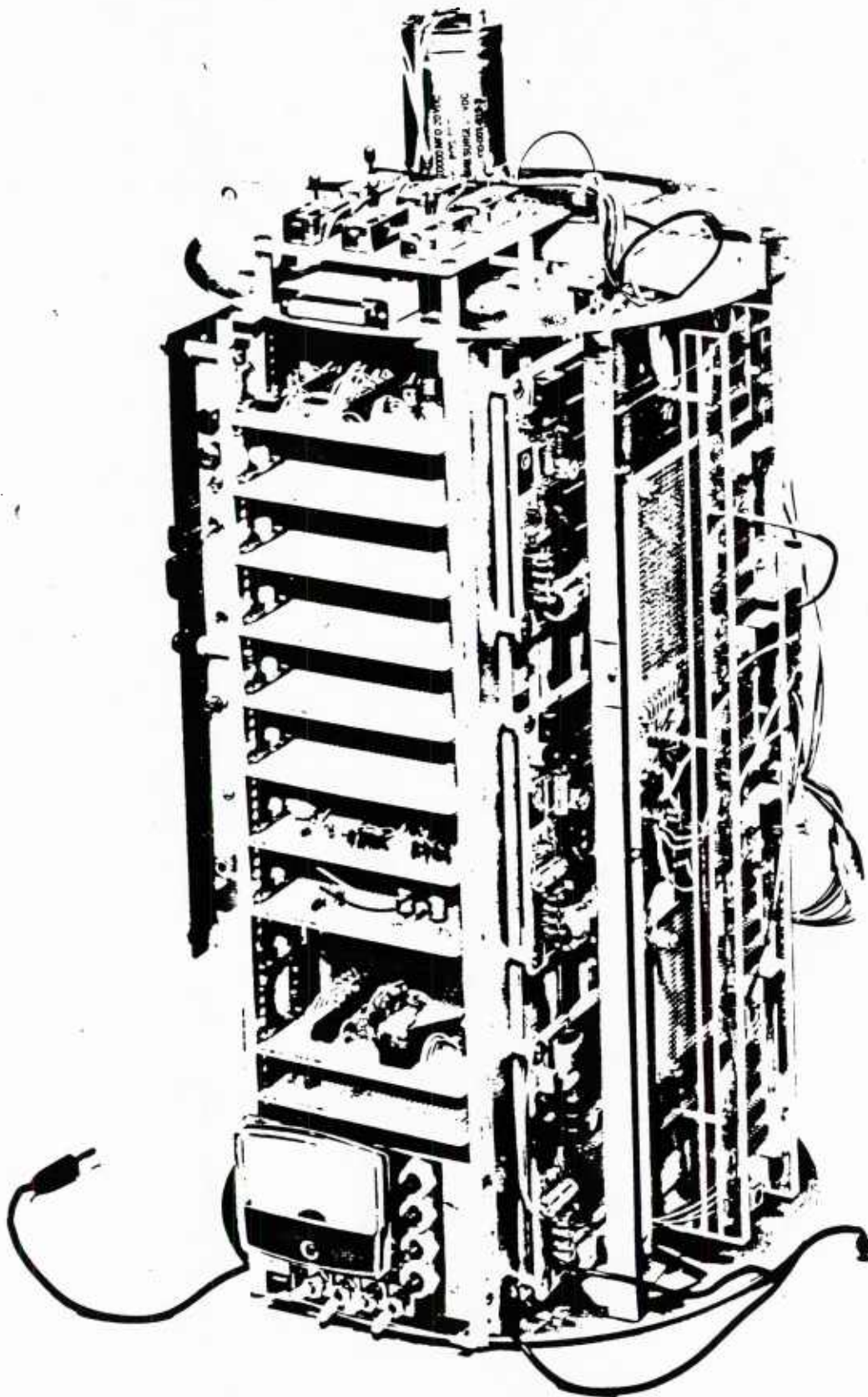
Figure 15.   Photo showing removable electronics package. Five of
the ultrasonic ranging modules are seen at the extreme right   of
the   assembly.   The foil side of the multiplexer circuitboard   is
just visible through the plexiglass on the swingout panel, behind
which can be seen CPU #2,   CPU #3,   and CPU #4,   mounted on   the
right   side of the card cage.   (Photo courtesy of Naval Surface
Weapons Center, White Oak, MD.)

down, or advises CPU #3 to power down the ranging system with the special command $FF.

The software is structured as shown in Figure 16. When energized by the Scheduler, CPU #3 does a power-on reset, initializes all ports and registers, and then waits for a command. When a command is latched into Port A of the 65SC22, a flag is set automatically that alerts the microprocessor, which then reads the command and determines the starting and ending identities of the rangefinders to be sequentially activated. The interface circuitry and ranging units are then powered up, and the Y Register is set to the value of the first transducer to be fired.

Subroutine PING is then called, which enables the particular channel of the multiplexer interface dictated by the contents of the Y Register. The VSW control line is sent high, which initiates operation of the selected ranging module. The software then watches the multiplexer output XLOG for indication of pulse transmission, before entering the timing loop. Each pass through the timing loop corresponds to a tenth of an inch in range measurement, in that sound travels exactly 0.20 inches in the time required for loop execution, at the system calibration temperature of 70 degrees F. The contents of the loop counter register RANGE thus correspond to the number of tenths of inches to the target. If this value ever exceeds the maximum specified range of the system, the software will exit the loop, otherwise the counter is incremented until MFLOG is observed to go high, indicating echo detection. Upon exit from the timing loop, the range value for that particular ranging module is saved in

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indexed storage, and Subroutine PING returns to the main program.

The Y Register is then incremented to enable the next ranging module in the sequence, and Subroutine PING is called again as before. This process is repeated until the Y Register equals the value of the ending index, signifying that all modules in the sequence specified by the Scheduler have been activated individually. CPU #3 then requests permission from the Scheduler to transmit all the stored range values via the RS-232. When acknowledged, the ranges are sequentially dumped out the serial interface and placed by the Scheduler in Page Zero indexed storage. Upon completion, CPU #3 checks to see if a new command has been sent down altering the ranging sequence, and then repeats the process using the appropriate starting and ending indexes. Thus the software runs continuously in a repetitive fashion, sequentially activating the specified ranging modules, converting elapsed time to distance, storing the individual results, and then finally transmitting all range data at once to the Scheduler, which is thus freed from all associated overhead.

In conclusion, the implementation of the sequential ranging array using a small dedicated microprocessor such as the MMC-02 offers several advantages to a mobile robot design. As seen above, the controlling microprocessor is unburdened of the lower level functions such as control line manipulation, timing, and conversion. Several prepositioned sensors allow data to be taken at a faster rate, with less power consumption, and fewer errors associated with actual sensor position than the alternative mechanically-positioned single-sensor systems. Improvements in
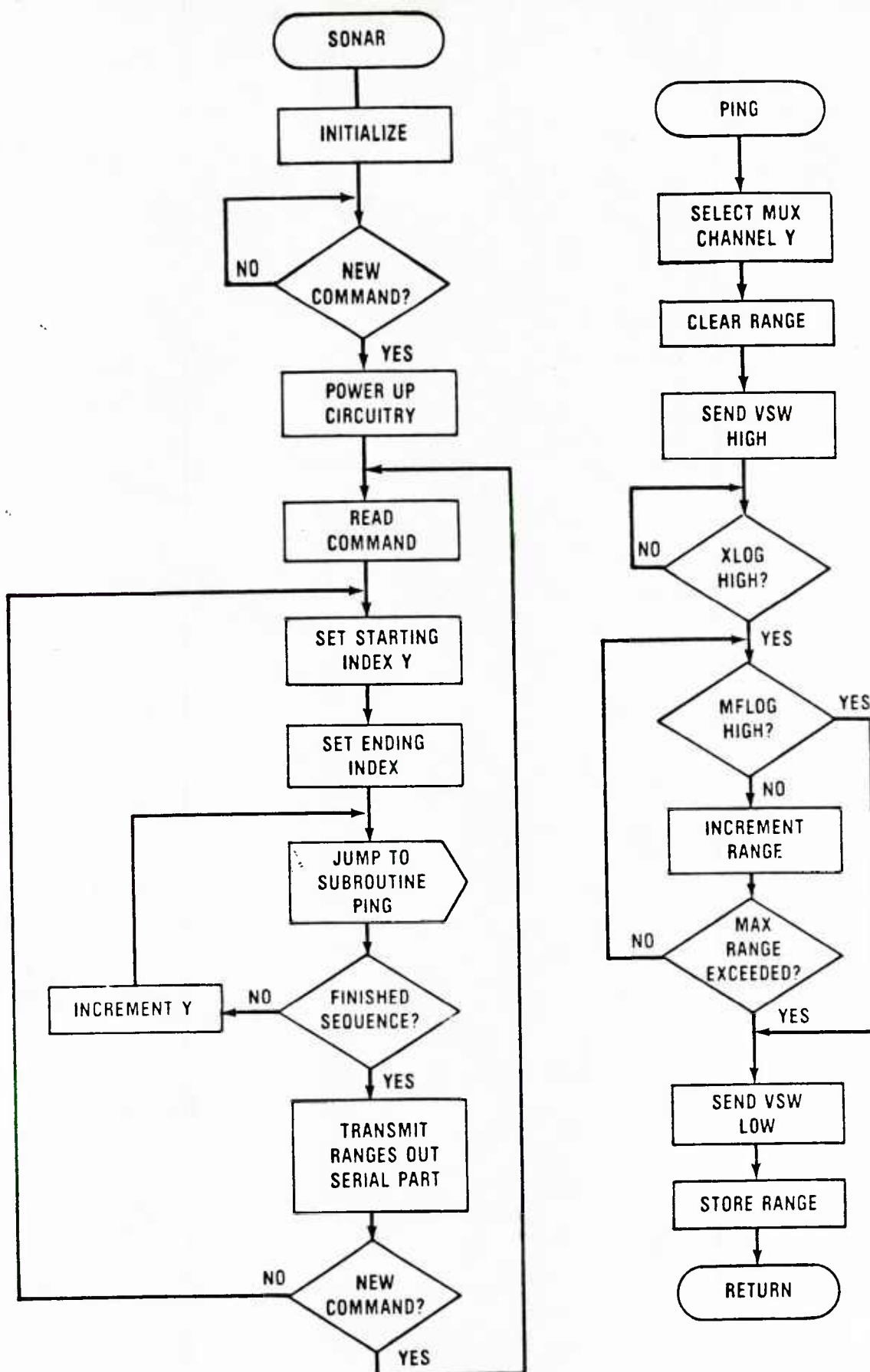
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Figure 16. Flowchart for the system software which runs on CPU #3. Subroutine PING activates and times individual ranging modules as dictated by the contents of the Y Register. Commands are sent down by the Scheduler to specify the sequence of modules to be activated.

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angular resolution can be gained through the use of beam splitting techniques, and temperature correction can be employed to increase range accuracy. The array thus exploits the properties of ultrasonic ranging for those applications best served, such as collision avoidance or object tracking, where absolute accuracies are not as important as is relative information. For other applications, such as navigation and map correlation in cluttered environments, where precision becomes an important factor, complementary sensors with appropriate characteristics must be brought to bear for optimum results. The relatively long wavelength, poor angular resolution, temperature dependence, and slow speed of sound in air become significant drawbacks, and near-infrared and laser based rangefinders should be considered as alternative approaches.

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